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Critical Current Parametrization and Short Sample Limit Calculation for the LHC IR Quadrupole Magnets

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Abstract:

As an update of a similar note on the "*Load Line and Short Sample Limit for HGQ1*" (TD 97-011) the short sample limits of the HGQ models 1-5 were recalculated using cable critical current measurement data supplied by BNL and using an updated critical surface parametrization. The former calculations were based on specified critical currents rather than measured ones. The critical surface parametrization used in the former note had not been verified on the type of conductors used for the HGQ cables. Furthermore small changes in magnet design have occurred since, raising the need to verify again short sample limit predicitions.
The critical surface parametrization (Devred and Bottura) proved to be convenient not only for the latest NbTi strands for the LHC dipoles, for which it was originally proposed, but also to predict with good accuracy the critical currents of SSC type strands of the HGQ cables. The critical current measurements on HGQ samples (provided by BNL) which went into model magnets are listed.
A preliminary study of the degradation of the strand critical current during cabling is reported to give an estimate of the typical degradation in HGQ cables.
The short sample limit calculations revealed that the former predictions for HGQ1 were sufficiently accurate. The refined values for short sample fields/currents of the different magnets, are close to each other and to the original design calculation (differences ~2%). Also, calculated short sample limits at 4.5K are close to values reached by magnets 2-3 after training at 1.9, and by magnet 5 during initial training at 4.5 (differences ~2%).

1) CRITICAL CURRENT MEASUREMENTS

As part of the usual quality control procedure samples of the cables destined to the HGQ (high gradient quadrupole) prototype program are measured at BNL. The critical current (Ic) measurements, as performed by BNL, are described in the US-LHC Technical Design Handbook[1]. Only few samples were measured at 1.9K. Especially the inner type cables showed severe training at 1.9K (and 8.7T). The following table summarizes the cable and strand Ic measurements for the conductors destined to the HGQ prototypes, as supplied by BNL. The dimensional data of the cable samples follow the specified values:

type	*strand #*	*strand Æ (mm)*	*Cu/Sc*	*strand twist*	*pitch (mm) / lay*	*width (mm)*	*mid thick (mm)*
in	38	0.808±0.0025	1.3±0.1	10±1.5 mm	114±5 / right	15.4±0.025	1.457±0.006
out	46	0.648±0.0025	1.8±0.1	13±1.5 mm	102±5 / left	15.4±0.025	1.146±0.006

BNL log#	CONDUCTOR ID	CRITICAL CURRENT (A)						COMMENT	MAGNET
		6T	**7T**	**8T**	**8T**	**9T**	**10T**		
inner		*4.22K*			*1.9K*				
3853	LHC-3-I-00589	19472	14410	9347					**1**
1642	virgin	526	389	248	663	527	395		
	extracted (average)								
3853	LHC-3-I-00596	19531	14453	9375					**2,3**
	virgin								
	extracted (average)								
3883	LHC-3-I-00634	18623	14151	9679	average of 2 measurements				**4,5**
	virgin								
	extracted (average)								
3900	LHC-3-I-00660	19313	14301	9290	premature quenches at 1.9K				**6**
1771	virgin	518		249					
	extracted (average)								
		6T	**7T**	**8T**	**8T**	**9T**	**10T**		
outer		*4.22K*			*1.9K*				
3858	LHC-4-F-00599	12538	9341	6144					**1,2**
	virgin								
	extracted (average)								
3884	LHC-4-F-00623	12435	9322	6209					**3,4**
16891703	virgin (average)	271.4	196	121	average of 4 measurements				
16971703	extracted (average)	258.2	193	127.3	average of 8 measurements				
3884	LHC-4-A-00635	11748	8670	5593					**5**
	virgin								
	extracted (average)								
3900	LHC-4-A-00661	12965	9627	6288	16382	13223	10084		**6**
1771	virgin	275		132					
	extracted (average)								

Table 1: BNL[2] critical current measurements on cables and strands (virgin and/or extracted, if available) destined to HGQ prototype magnets 1-6.

1 US-LHC Technical Design Handbook, editor J. Strait
2 personal communication A. Ghosh, BNL

2) PARAMETRIZATION OF THE CRITICAL SURFACE

The following NbTi Ic-parametrization, from A. Devred and L. Bottura [3] , combined with basic formulas from Lubell [4], has been found to fit best the experimental strand Ic-data.

$$T_c(B) = T_{c0}\left(1 - \frac{B}{B_{c20}}\right)^{\frac{1}{n}}$$

$$B_{c2}(T) = B_{c20}\left[1 - \left(\frac{T}{T_{c0}}\right)^{n}\right]$$

$$j_c(B,T) = j_{cREF}(4.22K,5T)\frac{C_0}{B}\left[\frac{B}{B_{c2}(T)}\right]^{a}\left[1 - \frac{B}{B_{c2}(T)}\right]^{b}\left[1 - \left(\frac{T}{T_{c0}}\right)^{n}\right]^{g}$$

The constants are:

T_{c0}	B_{c20}	n	C_0	a	b	g
9.2K	*14.5T*	*1.7*	*31.4*	*0.63*	*1*	*2.3*

The reference current density $j_{cREF}(4.22K,5T)$ is usually calculated from a measured value using the above relation "in reverse". $J_{cREF}(4.22K,5T)$ is typically 3000A/mm^2 for SSC and LHC type strands. A slight underestimation of the critical current at fields above 10T could be detected. A plot illustrating the predictive power of the formalism in the critical current vs. temperature case shows a similar pattern.
However, the comparison with other critical current parametrizations [5,6,7] revealed that the above shown formula is presently the best available fitting formalism.

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[3] "Review of Superconducting Dipole and Quadrupole Magnets for Particle Accelerators", A. Devred, DAPNIA/STCM 98-07, 1998
[4] "Empirical Scaling Formulas for Critical Current and Critical Field for Commercial NbTi", M.S. Lubell, IEEE Transactions on Magnetics 19, p. 754, 1983
[5] "Nb-Ti Alloy Superconductors-Present Status and Potential for Improvement", D.C. Larbalestier, Adv. in Cryog. Eng. Mat., Vol. 26, ICMC 1979
[6] "A New Critical Surface for RHIC NbTi", G. Morgan, BNL Memo 560-1 (RHIC-MD-261), jan. 1997
[7] "Load Lines and Short Sample Limit for HGQ model 1", G. Sabbi, Fermilab Note TD97-011, Apr. 1997

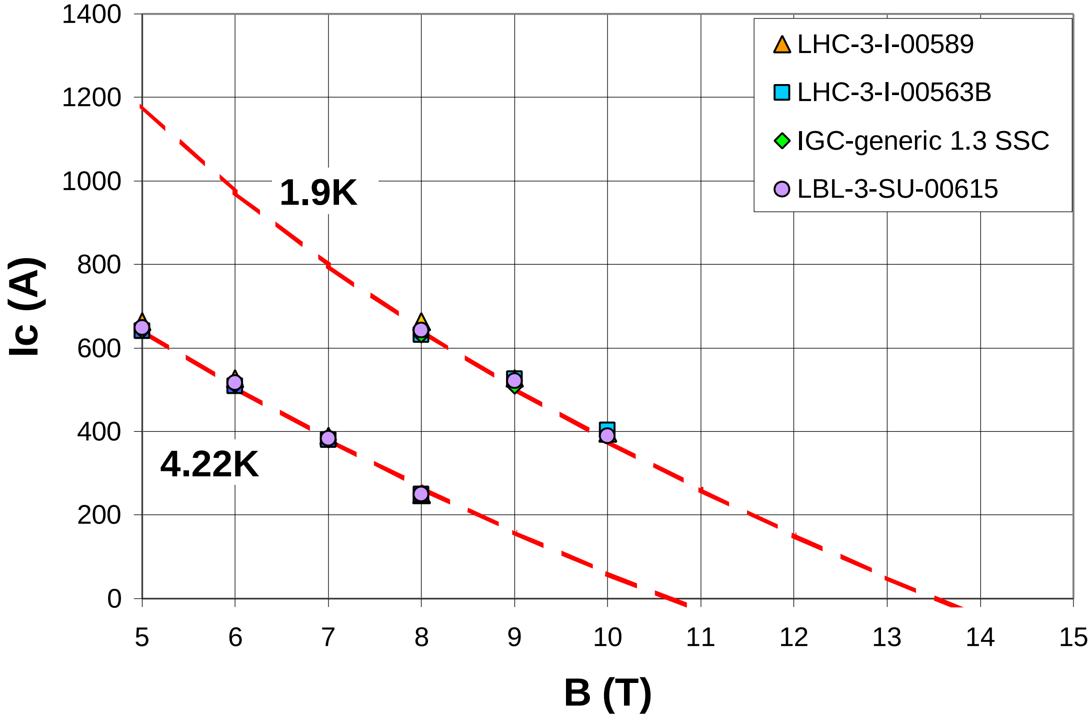

Figure 2: Critical current of inner type HGQ strands vs. magnetic field at 4.22K and 1.9K. The four samples are: 589, used in magnet 1, 563 an older HGQ R&D-cable using an IGC strand, a generic Cu/Sc ratio 1.3 SSC inner strand and a test-strand from Furukawa #615. The Ic(B) parametrization (dashed) is normalized on the 7T/4.22K measurement points.

In the course of HGQ cable R&D a considerable number of strands and cables have been produced and tested. Nevertheless, the above shown selection is representative in what refers to design as well as critical current. Special attention was dedicated to the development of “high Iron” content strands [8]. They have not been considered here.

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[8] “Development of Superconducting Strand for Low Beta Quadrupoles: FNAL P.O. No. B94240- Final Production Strand Report for Oxford Instruments- Superconducting Technology Strand”, P.J. Lee, A. Squitieri, B, Starch, W. Gabr-Rayan, C. Fischer, D. Vernon, R. Werner, D. C. Larbalestier

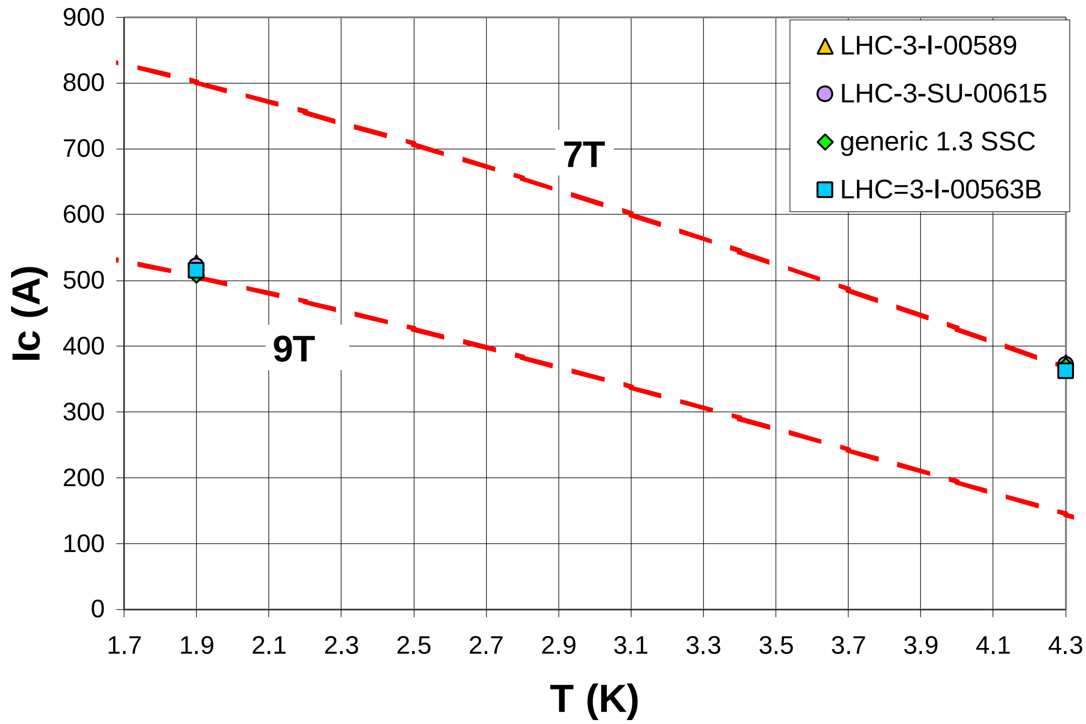

Figure 3: Critical current of inner type HGQ strands vs. temperature for 7T and 9T. The four samples are: 589, used in magnet 1, 563 an older HGQ R&D-cable using an IGC strand, a generic Cu/Sc ratio 1.3 SSC inner strand and a test-strand from Furukawa #615. The Ic(B) parametrization (dashed) is normalized on the 7T/4.22K measurement points.

3) DEGRADATION OF THE CRITICAL CURRENT BY CABLING

The degradation of the critical current density during cabling is difficult to estimate. It usually varies strongly between different types of cables and it can even vary considerably along one cable length. The most accepted way of estimating the degradation is to compare the average Ic of a certain number of strands extracted from the cable to that of a virgin strand (prior to cabling). Only 3 HGQ samples were tested in this way. One of them (sample 563B) showed a degradation of ~10%. Since it is exceptional with respect to its width and strand number it is not considered here. The other two samples, the inner type cable #581 and the outer type cable #623, showed a degradation of ~4% at 4.2K and 6T (see figure).
Another way of assessing the degradation uses a comparison of a "virgin-strand" and a cable measurement. With respect to this technique more data are available, namely #589, #660 and #661 (see table). A drawback of this technique is that one compares self-field corrected cable Ic measurements with not self-field corrected (and therefore underestimated) strand Ic measurements. Therefore, the typical range of 1-2% difference

found this way has to be corrected to higher values to obtain the effective degradation. In what refers to RHIC strands this correction was typically +4%[9].

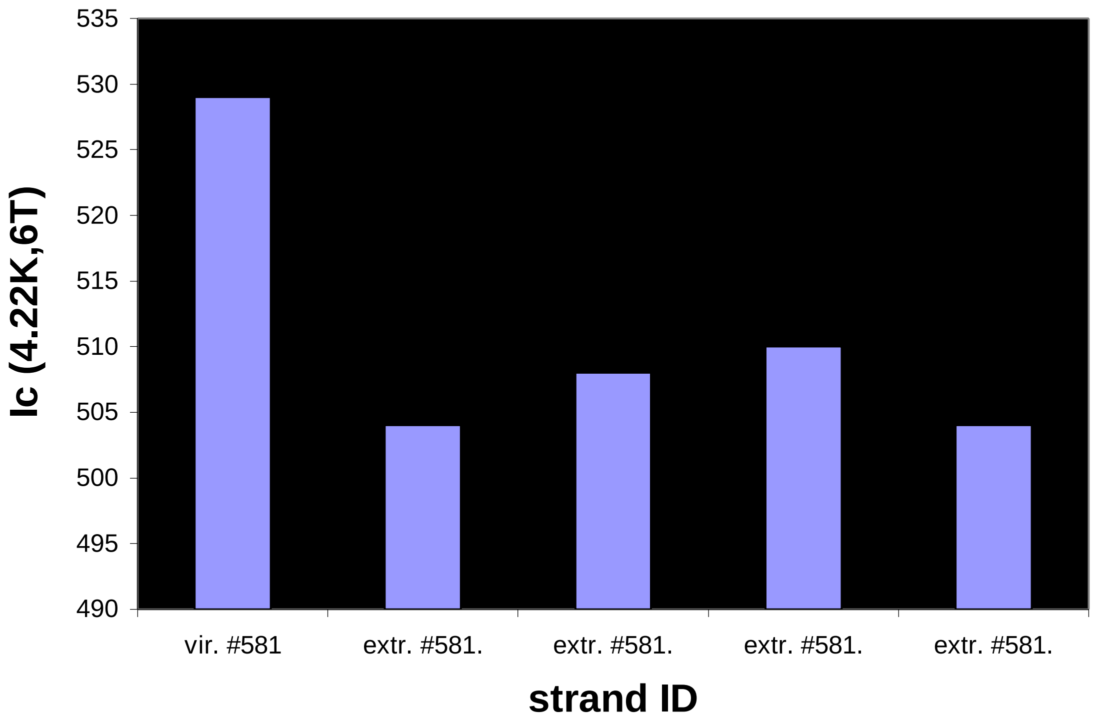

Figure 4: Degradation study on cable sample 581. The critical current of strands prior to cabling ("vir") and after cabling ("extr.") are compared at 4.2K and 6T. From this plot the average degradation can be estimated to ~4%.

cable	BNL log	Ic cable	BNL log	Ic virgin strand x Nr. of strands in cable	difference [%]
LHC-3-I-00589	3853	19472	1642	19988	**2.6**
LHC-3-I-00660	3900	19395	1771	19648	**1.5**
LHC-4-I-00661	3900	12928	1771	13000	**0.5**

Table 2: Comparing the cable critical current with the critical current of the strand before cabling. The difference found for these 3 samples is 1-2%. Cable and strand Ic measurements cannot be compared directly because of the difference in magnetic field estimation. Therefore the "difference" is commonly not called "degradation".

4) SHORT SAMPLE LIMIT PREDICTIONS

Using the above mentioned Ic parametrization the critical currents and the slopes of the critical current versus magnetic field curves of the cables that went into different HGQ

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[9] ***personal communication by A. Ghosh, BNL***

models at different magnetic fields and temperatures can be predicted from a measurement point at e.g. 7T and 4.22K (taken from table 1).

	Ic(T,B) [kA] and $(dIc/dB)_{T,B}$ [kA/T]					
Cable ID	**7T/4.22K**		**7T / 4.5K**		**10T / 1.9K**	
LHC-3-I-00589	*14.41*	*-4.71*	*12.30*	*-4.48*	*14.25*	*-4.59*
LHC-3-I-00596	*14.45*	*-4.71*	*12.33*	*-4.52*	*14.29*	*-4.59*
LHC-3-I-00634	*14.15*	*-4.63*	*12.07*	*-4.41*	*13.99*	*-4.52*
LHC-3-I-00660	*14.30*	*-4.67*	*12.20*	*-4.44*	*14.14*	*-4.56*
LHC-4-F-00599	*9.341*	*-3.03*	*7.970*	*-2.89*	*9.238*	*-2.99*
LHC-4-F-00623	*9.320*	*-3.03*	*7.952*	*-2.89*	*9.217*	*-2.99*
LHC-4-A-00635	*8.758*	*-2.85*	*7.473*	*-2.71*	*8.662*	*-2.81*
LHC-4-A-00661	*9.628*	*-3.17*	*8.215*	*-2.99*	*9.521*	*-3.08*

Table 3: Calculated critical currents and critical gradients for the cables used in some HGQ model magnets.

Using cable and not strand measurement-data for the Ic extrapolation hopefully generates estimates which include the effect of degradation, which in most cases will be independent of temperature and magnetic field ("broken filaments"). A calculation based on strand measurements has to be reduced by an empirical estimation of the degradation, as discussed in the former chapter. However we do not consider the latter technique to be reliable enough as a consequence of the small number of degradation studies conducted on HGQ type cables.

The short sample limit is calculated from the smallest crossing point of the straight section and end section inner and outer coil peak-field load lines (including iron saturation) and a linearized inner and outer conductor jc(B) relation deduced from the data in the table above. This procedure is described in details in [10]. The following table summarizes the magnet 1-5 short sample limit predictions.

Resuming the short sample calculations we conclude that the short sample limits predicted from specification values of jc and magnet load-lines [11] agree well with the values now predicted from real cable Ic measurements as well as revised magnet parameters (given in the following tables).

At 1.9 K:

Bmx(T)/Imx(kA)	HGQ01	HGQ02	HGQ03	HGQ05
Body, inner	9.94/14.50	9.95/14.51	9.95/14.51	9.90/14.44
End, inner	9.84/15.0	9.84/15.0	9.84/15.0	9.78/14.96
Body, outer	8.28/14.39	8.28/14.39	8.27/14.38	8.09/14.03
End, outer	8.40/14.02	8.26/14.42	8.26/14.42	8.07/14.08

10 "Load Lines and Short Sample Limits for HGQ Model 1", G. Sabbi, Fermilab, Technical Division Note TD97-011, Apr. 97

11 "Magnetic Field Analysis of the first Short Models of a High Gradient Quadrupole for the LHC Interaction Regions", G. Sabbi, J. Strait, A. Zlobin, S. Caspi, Proceedings of the MT15, Part I, p. 171, Science Press, Bejing, China, 1999

Iss (kA)	14.02	14.39	14.38	14.03
Gss (T/m)	250.15	256.24	256.11	250.27

Remarks: expected Iss for HGQ01 and 2 were published as 13.9 and 14.2 kA, respectively. All refined values are within +/-200 A (+/-1.5%) from those ones. Variations are mainly due to Cu/Sc in different wires (still, all within specs), except for HGQ01, which is limited by end field.

At 4.2 K:

Bmx(T)/Imx(kA)	HGQ01	HGQ02	HGQ03	HGQ05
Body, inner	7.70/11.11	7.71/11.12	7.71/11.12	7.67/11.06
End, inner	7.6/11.6	7.6/11.6	7.6/11.6	7.56/11.56
Body, outer	6.44/11.0	6.44/11.0	6.43/11.03	6.29/10.78
End, outer	6.50/10.85	6.40/11.17	6.39/11.16	6.25/10.90
Iss (kA)	10.85	11.04	11.03	10.78
Gss (T/m)	195.55	198.82	198.68	194.24

Remarks: Iss in magnet body was calculated as 10.99 kA. All refined values are within +/-200 A (+/-2%) from that one.

At 4.5 K:

Bmx(T)/Imx(kA)	HGQ01	HGQ02	HGQ03	HGQ05
Body, inner	7.37/10.62	7.38/10.63	7.38/10.63	7.34/10.57
End, inner	7.27/11.08	7.27/11.11	7.27/11.11	7.23/11.05
Body, outer	6.13/10.49	6.13/10.49	6.12/10.48	5.98/10.23
End, outer	6.18/10.32	6.08/10.62	6.08/10.61	5.93/10.36
Iss (kA)	10.32	10.49	10.48	10.23
Gss (T/m)	186.33	189.17	189.04	184.62

Remarks: short models reached short sample at ~4.5K after training at 1.9. Scaled values at 4.5 are HGQ02=10.7 kA, HGQ03=10.6 kA, HGQ05=10.1 kA. These measured values are within 200 A (2%) from calculations.

Table 4: Predicted short sample limits of HGQ model 1-5 in kA at 1.9K, 4.22K and 4.5K.